

Traceability, Calibration, and Measurement Uncertainty Issues Regarding Coordinate Measuring Machines and Other Complex Instruments

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A variety of market forces, such as the globalization of the economy, increasing use of international standards, tighter product tolerances, and an increasing concern for quality control, are slowly but steadily raising awareness of issues including traceability, calibration and measurement uncertainty. This paper discusses the relationship between these issues with emphasis on dimensional metrology, especially coordinate measuring machines (CMMs), in a manner intended to be informative to understanding traceability for industrial measurements.

Traceability

Historically, traceability has meant the ability to produce a paper trail of calibration reports starting at the measurement or artifact of concern and typically leading back to a national laboratory. In the 1990's the international definition of traceability increased the requirements as described below.

Traceability (VIM 6.10) [1]: property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties.

Whereas "old traceability" was focused on documenting the "unbroken chain of comparisons", this "new traceability" additionally requires the statement of measurement uncertainty. Hence a gauge block calibration laboratory must not only use calibrated master gauge blocks when reporting the deviation from nominal length of a customer's block, but the uncertainty of the measurement must now also be reported. This additional accuracy information is increasingly valuable from an economic viewpoint in order to determine the price versus performance of various calibration alternatives. This is particularly useful since many manufacturing enterprises are geographically widely dispersed and often outsource this type of function. To support the new traceability efforts the laboratory accreditation industry has emerged, with the examination of uncertainty statements as one of its primary functions.

While laboratory accreditation programs are slowly bringing calibration facilities into the new traceability system, the issue of traceability often reaches well beyond the calibration laboratory and onto the factory floor. Market forces and contractual requirements, particularly involving the government, may require the measurements on products to be traceable. This enormously complicates life for the industrial metrologist. Unlike the calibration laboratory where a small number of highly idealized artifacts are measured under controlled conditions, industrial facilities produce huge numbers of complex components with a large number of toleranced attributes, measured under conditions that are continuously changing both environmentally and with respect to human and capital resources. CMMs well represent this difficulty, as they are flexible industrial gauging systems that can measure an almost endless number of different

measurands, in a wide variety of positions and orientations, with many different probe / stylus configurations and point sampling strategies, and are used by many different operators under diverse environmental conditions.

Measurement Uncertainty

Measurement uncertainty is a quantitative expression of one's belief in the closeness of a measurement result to the "true value" of the measurand. The internationally accepted method for expressing measurement uncertainty is given in the *Guide to the Expression of Uncertainty in Measurement* [2]. In this paper, the term measurement uncertainty is used to mean the expanded uncertainty U with a coverage factor of two ($k = 2$). Hence a measurement result stated $y \pm U$ is generally interpreted as defining an interval that contains 95 % of the reasonable values that can be attributed to the measurand.*

To emphasize the diversity of CMM measurement capability, the term task specific measurement uncertainty is sometimes used. The motivation of this term is to stress the distinction between the results of a CMM performance evaluation test, typically used as a specification for the buying and selling of CMMs, and the measurement uncertainty associated with a particular workpiece feature measured in a particular manner under industrial conditions. In particular, the results of a CMM performance evaluation cannot (in general) be used directly to state the uncertainty of a CMM measurement, and typically the performance evaluation and industrial measurement will not even involve the same measurand. Hence, there is no simple "one size fits all" measurement uncertainty statement for general CMM measurements.

The difficulty in evaluating the "task specific" measurement uncertainty for CMM measurement results arises from the enormous variety of measurands and "measurement conditions" that might occur on a single workpiece, e.g. an engine block. By measurement conditions we mean the values of all influence quantities of the measurement. (An influence quantity is any factor that affects the measurement result.) Some of these factors are under direct control of the CMM operator, such as the sampling strategy (the number and location of the measured points on the part surface), the probe and stylus configuration, the location of the workpiece in the CMM workzone and so on. The operator may have little or no control over other factors, such as the temperature and fixturing of the workpiece or its surface roughness and form error. It is the collection of all these influence quantities that must be considered, and their impact on the measurement result evaluated, in order to compute the measurement uncertainty.

Calibration

The starting point for computing measurement uncertainty begins with the known information provided by the instrument calibration. An instrument calibration typically includes (1) administrative and procedural documentation, e.g. as required by ISO Guide 25 [3], and involves such issues as the serial numbers of the master gauges in use; (2) a statement of the measurand being calibrated; (3) the calibration result together with an uncertainty statement; and (4) a statement regarding the validity conditions of the calibration. (The validity conditions are the

* The 95 % level of confidence associated with a coverage factor of $k = 2$, assumes that the values that could be reasonably assigned to the measurand are normally distributed, the degrees of freedom in the uncertainty budget are large, all systematic errors have been corrected, and that all relevant uncertainty sources have been well characterized.

value(s) of the relevant influence quantities under which the results and uncertainty stated in the calibration report are valid.) When the instrument is used for subsequent measurements it is the calibration process that connects the measurement result back to the SI unit, hence providing this crucial link required for traceability.

The instrument calibration involves (in addition to other factors) the evaluation of each subsystem where the metric (e.g. the unit of length) is generated. For a general purpose CMM, the metric is established by each of the three scales and also by the probe calibration artifact (that sets the size of the stylus tip). Hence the calibration of the three linear scales (e.g. by a step gauge), a measurement of a feature of size, and the use of some sort of calibrated thermometer, is the minimum necessary to connect the CMM back to the SI unit of length. (The length of an object is defined at 20 °C by international agreement, hence except for gauges with zero thermal expansion coefficient, a temperature measurement is needed to complete the connection to the SI unit.) As described below, such a minimal calibration generally does not result in sufficient information to be useful in evaluating the uncertainty of typical industrial measurements.

The general problem with CMM measurement uncertainty evaluation is that the measurand and validity conditions of the calibration are usually very different from the measurand and measurement conditions of the specific feature of interest. For example, the measurand in a CMM calibration may be a point-to-point length measurement along a particular line in the CMM workzone while the measurand of industrial interest may be the concentricity between two bores.

This raises the general issue of the degree of “closeness” between the results of the calibration and the industrial measurement under consideration. We use the term closeness in a qualitative manner, but it corresponds roughly to the amount of additional work that must be performed to arrive at a measurement uncertainty statement for the industrial measurement when starting with the calibration information. From a qualitative mathematical viewpoint, one can picture a large hyperspace with each dimension corresponding to an influence quantity or the measurand under consideration. The calibration measurand and validity conditions define a point or volume in this hyperspace, and the industrial measurement also defines a point or volume in the hyperspace. If these two regions are near (or overlap) with each other then less information and calculation are required to get from the calibration to the measurement situation than if these regions are far apart; see Figure 1.

For example, suppose the CMM calibration involved measuring the bidirectional point-to-point length error at 20 °C along three lines in the CMM workzone, each parallel to one of the axes of the CMM. Suppose the measurement of interest was also a bidirectional point-to-point length along one of these lines at 20.1 °C. The calibration and measurement situations are close to each other and a simple additional uncertainty contribution must be computed to account for the small difference in the thermal influence quantities. Similarly, if the measured length was parallel to but slightly displaced from the workzone line where the calibration occurred a small (perhaps negligible) additional uncertainty contribution would need to be included in the uncertainty statement. However, if the measurement of interest is the cylindricity of a large bore inclined at a compound angle in the workzone then the calibration and measurement situations are far apart. In this case much additional information and computation are required to arrive at a

measurement uncertainty statement when starting with the calibration results. This additional information might include a probe performance test, a CMM volumetric performance test, computational information on how to assess the impact of the point sampling strategy on the cylindricity measurand, information on the form error of the cylinder and so forth. Hence this simple and straightforward calibration, while providing connection to the SI unit, is insufficient to evaluate the uncertainty of most measurements of industrial interest, i.e. the calibration and measurement situations are far apart in hyperspace. Thus while the CMM calibration may establish the connection back to the SI unit, it is usually insufficient to provide (without further information) a task specific uncertainty statement.

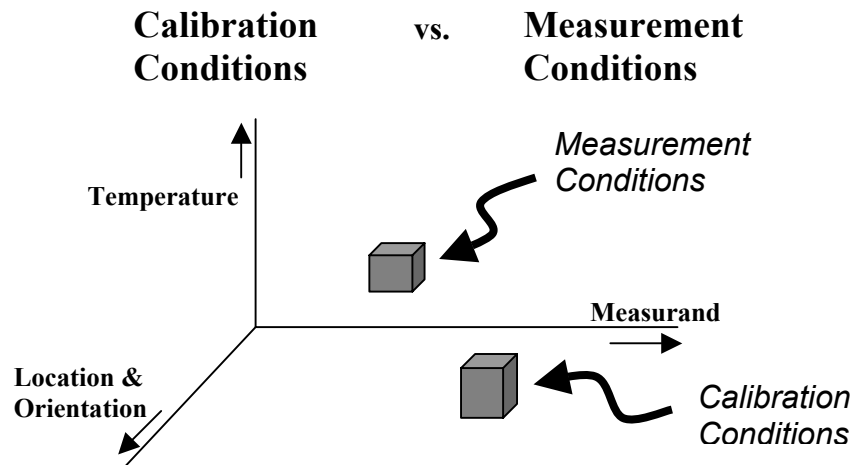


Figure 1. Illustration of the relationship between the influence quantities and measurands of the calibration and measurement cases; while in reality a large number of influence quantities are involved, for clarity only three factors are shown in the figure.

At the opposite extreme lies the calibration method of “substitution” or “comparison” where a calibrated artifact nominally identical to the workpiece is repeatedly measured by the CMM in exactly the same manner as the workpiece is intended to be measured in order to assess the measurement uncertainty [4]. The CMM is now calibrated to measure this particular workpiece in this particular manner. The advantage of this method is that the calibration and measurement situations are nearly identical, i.e. very “close” in hyperspace. Hence the results of the calibration can be applied directly to the specific measurement of interest providing the measurement result with a connection to the SI unit and an applicable uncertainty statement. The major disadvantage is that it requires a calibrated artifact for every type of workpiece under consideration, and the calibration process must be conducted anew if any influence quantity (e.g. stylus length) is changed; hence the method badly lacks generality.

The Measurement Problem

While a virtue of the CMM is the almost unlimited combination of workpiece features that can be inspected, this becomes a significant headache when trying to establish traceability of these measurements. Typically neither the measurand, nor the validity conditions of the CMM calibration are appropriate for a particular measurement under consideration.

In the special case of the substitution method, when the validity conditions include the measurement conditions, then the uncertainty statement from the calibration can be applied

directly to the workpiece. Unfortunately the specialized nature of the substitution method generates a large amount of work and costs associated with inspecting a complex workpiece. The validity conditions of the substitution method can be enlarged by repeating the measurements of the calibrated artifact over a broad range of conditions that are expected to encompass all those of the subsequent (and nominally identical) workpiece measurements. This allows the uncertainty statement to be applied to a series of workpiece measurements, each with somewhat different measurement conditions (as is typical in factories) at the price of an increased uncertainty value.

The more typical situation is that the metrologist must collect additional information beyond that of the CMM calibration report, and then construct an uncertainty budget that depends on the details of the measurement. Furthermore, the process of converting the CMM calibration results from the measurand of the calibration to the measurand of the workpiece can be very difficult. Among the more general methods developed to address this issue is computer simulation of the measurement. In this method, the CMM user provides input to a software program describing numerous details of the specific measurement under consideration and performance characteristics of the CMM in use. In some simulation programs the CMM performance data may be based on manufacturer's specifications and in other cases it may be based on a specific performance test results. In either case, a major benefit is to convert general CMM performance information, typically based on simple measurands, into CMM performance values for the specific workpiece measurand of interest. Similarly, numerous other influence quantities, such as the point sampling strategy, are simultaneously included into the uncertainty calculation. A result of this is, in effect, a computer generated substitution method, without the need for a specialized calibrated artifact. The simulation program gains the connection to the SI unit from the CMM performance data (i.e. the CMM calibration) and generates the uncertainty statement by repeated (Monte Carlo) simulations of the specific measurement task taking into account the possible variation (i.e. uncertainty) of the relevant influence quantities. Figure 2 illustrates the tradeoffs of various calibration methodologies with respect to subsequent measurement applicability.

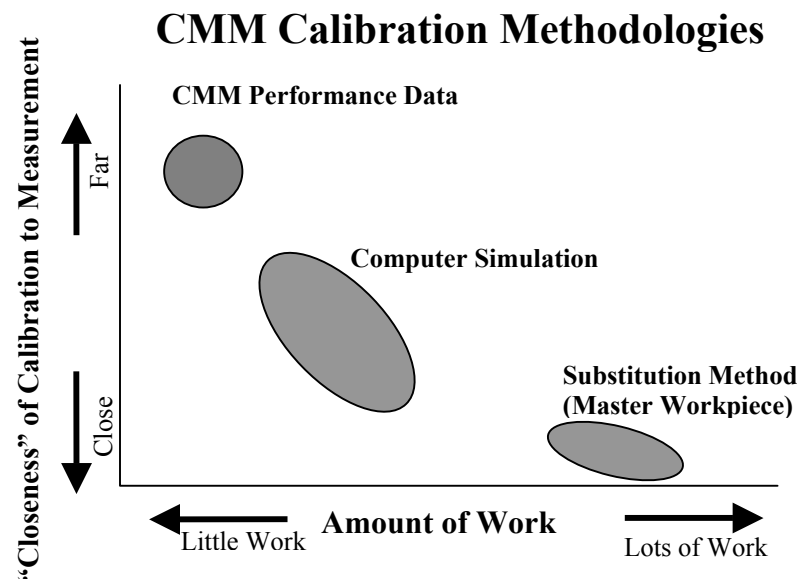


Figure 2. Schematic illustrating the general relationship between different CMM calibration approaches and their applicability to subsequent measurements.

A major advantage of the simulation approach is the ability to predict the accuracy, i.e. evaluate the uncertainty, of various different measurement methods of inspecting a workpiece. Figure 3 illustrates examples of computing the uncertainty using simulation of a small ring gauge, as compared against the measurement error. In each case several different sampling strategies (location of the probing points) are considered. Additionally, the standard deviations resulting from repeated measurements are similarly shown.

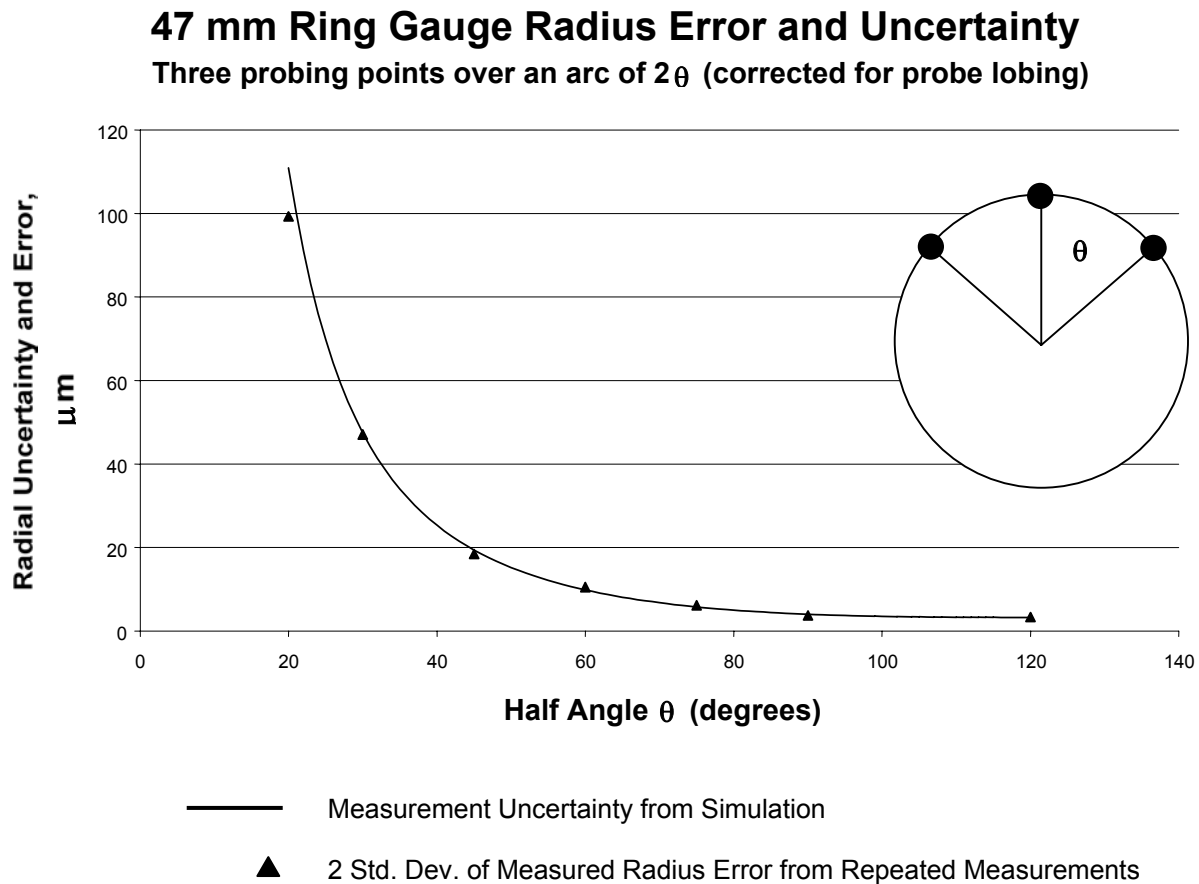
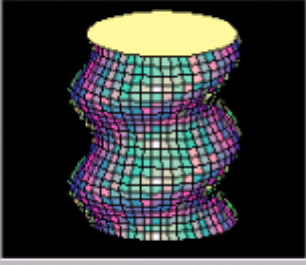






Figure 3. A comparison of the evaluated expanded uncertainty based on computer simulation with twice the standard deviation of measurement errors of a small ring gauge, as a function of different sampling strategies given by the half angle θ .

The extent to which computer simulation can faithfully reproduce the actual substitution method depends both on the number of relevant influence quantities that are included in the simulation and on the manner in which these effects are combined. The metrologist must estimate many of these factors. Figure 4 illustrates one software method of describing imperfect form error of the workpiece [5].

User Query

Shape of Selected Form


Form Type	Order of Theta	Order of Z	Turns	Amplitude
 Systematic	1	0	2	10
 Systematic	0	1	0	10
 Random	NA	NA	NA	3
 Undefined				

Quadrature Sum 14.4568
Left click on the selected form to edit the amplitude

Definition of Selected Form

☐ Random
☐ Systematic

Order of Theta: 0 1 2 3 4 5 6 7 8 9
Order of Z: 0 1 2 3 4 5 6 7 8 9
Turns:

Done Cancel

Figure 4. An example of user generated information for computer simulation of measurement uncertainty; in this example various workpiece form errors can be combined with the nominal geometry; the figure shows a helical form error imbedded on a cylinder.

Summary

The modern definition of traceability intimately links the concepts of calibration (providing connection to the SI unit) and measurement uncertainty. In the typical CMM measurement problem the measurement under consideration bears little resemblance to the measurand or validity conditions of the CMM calibration. Consequently, the metrologist must develop methods to combine the known CMM calibration information together with the measurement specific factors to generate a task specific uncertainty statement.

The entire traceability chain for a typical CMM measurement is shown in Figure 5. The first three steps, generation of the atomic clock, realization of the unit of length by the iodine stabilized laser, and the calibration of metrology lasers, are typically the responsibility of national laboratories. For the next three steps, there is a significant worldwide research effort underway to develop inexpensive calibrated artifacts, efficient CMM calibration procedures, and methodologies to estimate task specific measurement uncertainty.

CMM Traceability Chain

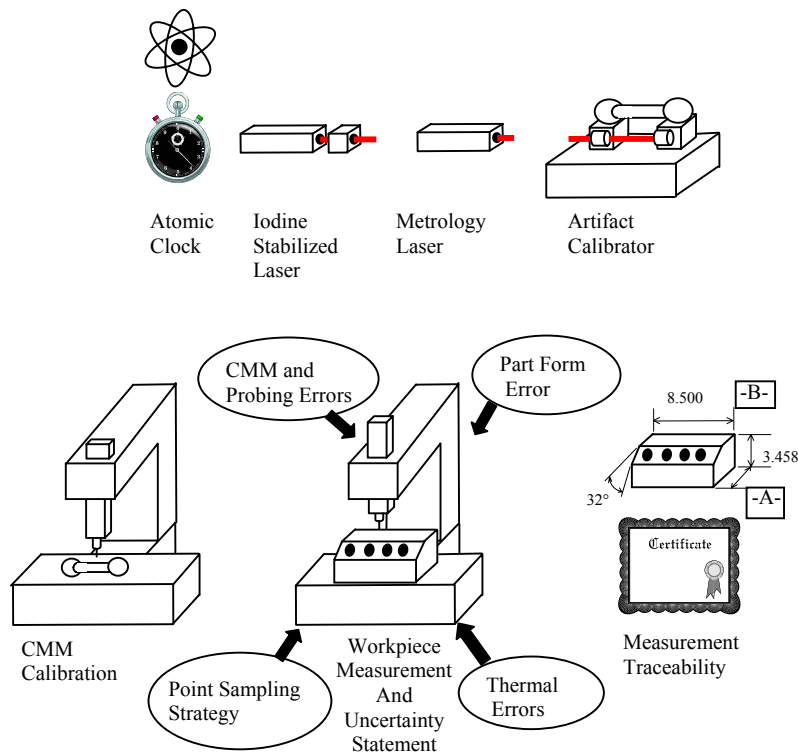


Figure 5. A typical traceability chain for CMM measurements

Acknowledgments

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